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RELEASE OF TECTONIC STRAIN BY LARGE UNDERGROUND NUCLEAR DETONATION

R. M. Turpening

Michigan University

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January 1973

FINAL REPORT

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UNIVERSITY OF MICHIGAN 1817

GEOPHYSICS GROUP · INFRARED AND OPTICS DIVISION
Willow Run Laboratories
INSTITUTE OF SCIENCE AND TECHNOLOGY

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13. ABSTRACT

This report describes an attempt to observe SH waves from several large underground nuclear explosions at first-zone distances (<600 km) from each event. The data base was supplemented by seismograms from the World Wide Standard Station Network and Canadian Network. Good SH arrivals were observed at the shorter ranges (<250 km) but not at ranges between 250 km and ≈1800 km.

In an effort to detect the arrival of any S waves (SV or SH) within this "shadow-zone," a flat-layered earth approximation was assumed (with hence critically refracted S-wave paths), and particle motion diagrams were then constructed. (The flat-layered earth hypothesis suggests small angles of incidence and therefore, rectilinear particle motion.) Such rectilinear motion was observed and in several "shadow-zone instances, arrival times were consistent with the model chosen.

The strong SH motion observed at shorter ranges appears to indicate that a "non-explosive" type of source mechanism occurred during the event. This possibility tends to be confirmed by several observations of first-arrival P waves with rarefaction motion.

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S waves						
Near-zone						
BENHAM						
BOXCAR						
FAULTLESS						
HANDLEY						

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II

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1 INTRODUCTION

The generation of shear waves by explosive sources has long been of interest to the seismological community. That such waves have been observed has never been doubted; however, questions about their generation have persisted.

With four nuclear explosions (HANDLEY, BOXCAR, BENHAM, FAULTLESS) used as data sources, this report is based upon a display of 29 three-component, L-7 system seismograms recorded at relatively short distances (96.6 km to 587.0 km), and supplemented (except for HANDLEY*) by data from 21 stations belonging to the World Wide Standard Station Network (WWSSN) and the Canadian Network.

While amplitude information was taken from all of the WWSSN records, only those records from stations lying on the same approximate azimuth as the primary, close-in, L-7 stations are displayed. Interpretation of the WWSSN seismograms for these and other events have been reported by Nuttli (1969) and are not elaborated upon.

Figures 1-8 indicate the site of each nuclear event as well as the map locations of all stations utilized for purposes of this report. Tables 1-4 give both event and station coordinates as well as distances and azimuths. In each table the abbreviations for stations listed above the solid line were devised by the author to facilitate making the maps; conventional WWSSN and Canadian abbreviations are used for other stations.

2 INSTRUMENTATION

All instruments for those stations listed above the solid line in Tables 1-4 are the L-7 three-component packages described by Navarro, et al. (1967) [1]; Ref. 2 gives package response curves. The instruments for stations listed below the solid line are the standard, long-period systems used at all of the World Wide Standard Network Stations (see Ref. 3 for response curves) and at Canadian Network stations (see Refs. 4a and 4b for calibration curves).

*No WWSSN data was available on the HANDLEY event.

FIGURE 1. FIRST-ZONE SEISMIC STATIONS FOR HANDLEY. Any plus and minus signs indicate P-wave first-motion polarity.

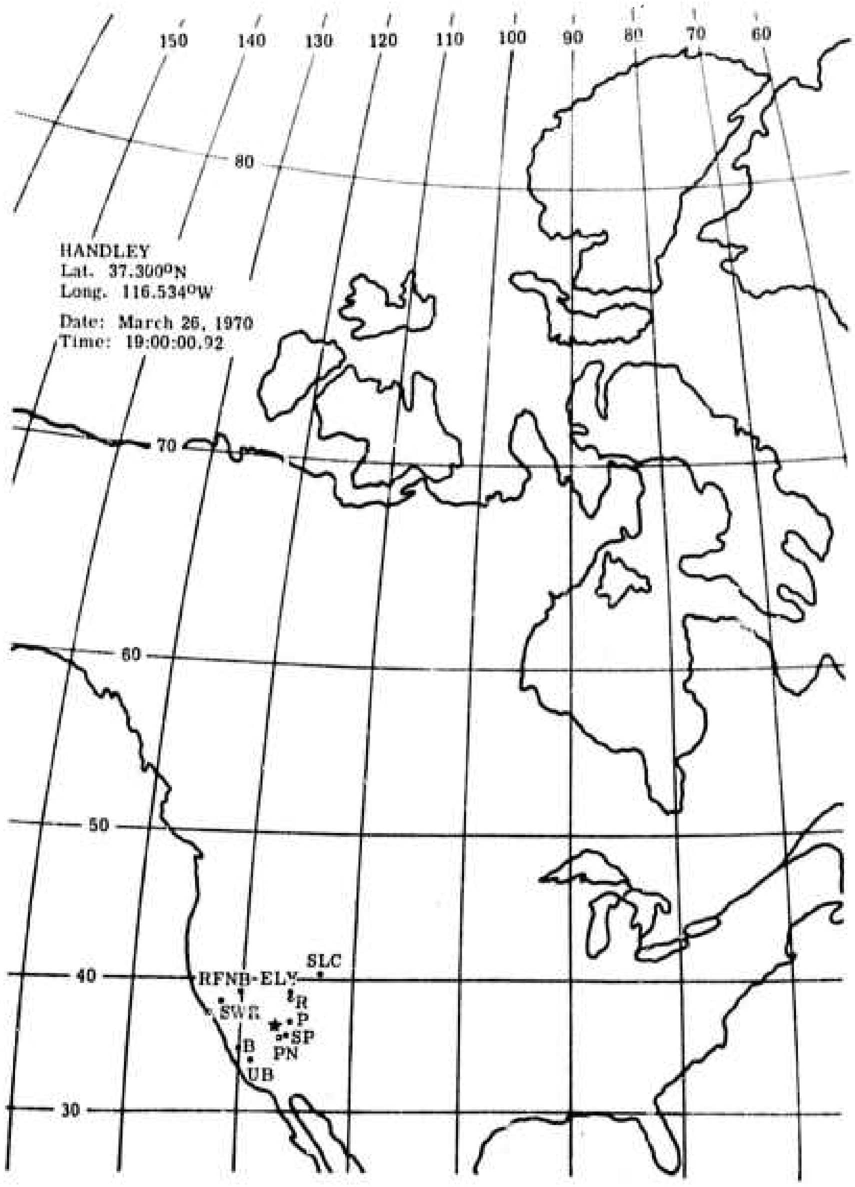

FIGURE 2. FIRST-ZONE AND WORLDWIDE STATIONS FOR HANDLEY

FIGURE 3. FIRST-ZONE SEISMIC STATIONS FOR BOXCAR. Any plus and minus signs indicate P-wave first-motion polarity.

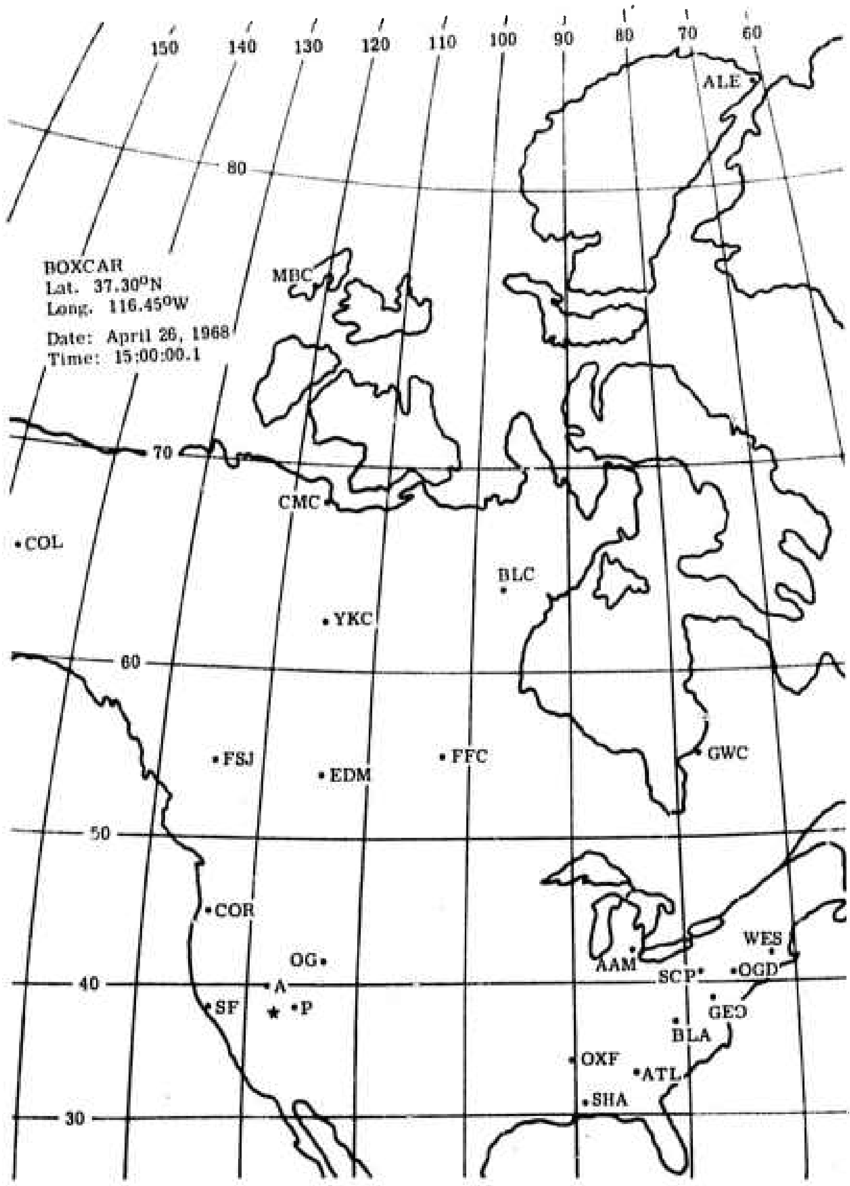

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FIGURE 6. FIRST-ZONE AND WORLDWIDE STATIONS FOR BENHAM

FIGURE 7. FIRST-ZONE SEISMIC STATIONS FOR FAULTLESS. Any plus and minus signs indicate P-wave first-motion polarity.

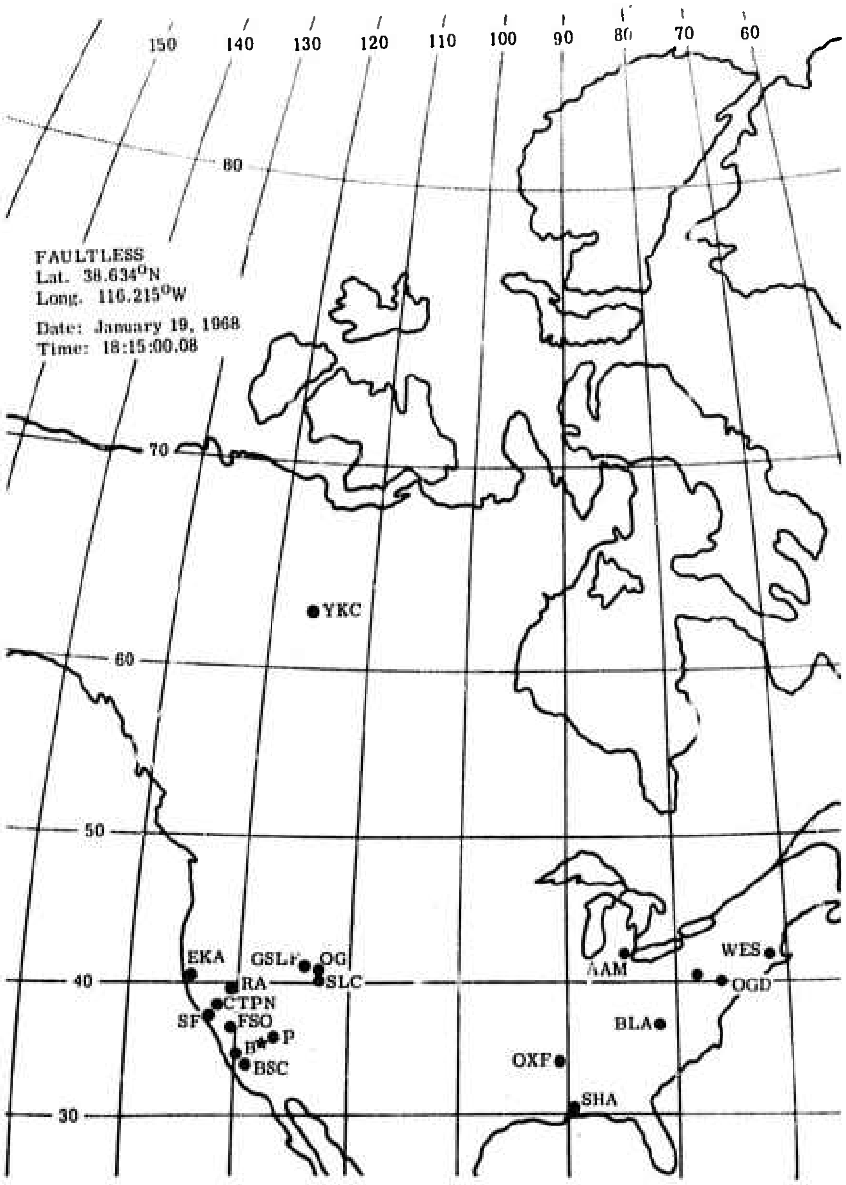

FIGURE 8. FIRST-ZONE AND WORLDWIDE STATIONS FOR FAULTLESS

TABLE 1. STATION LOCATIONS, DISTANCES, AND AZIMUTHS FOR EVENT HANDLEY

Latitude 37.300°N, Longitude 116.534°W

March 26, 1970
19:00:00.2 GMT

Station	Site Coordinates		Distance		Azimuth
	°N	°W	Deg.	Km	Epicenter to Station
Pahrump (PN)	36.215	115.983	1.170	130.1	157.6°
Squires Park (SP)	36.174	115.139	1.587	176.5	134.7°
Pioche (P)	37.937	114.450	1.773	197.1	68.4°
Ely (ELY)	39.131	114.892	2.239	249.0	34.8°
Ruth (R)	39.258	114.998	2.298	255.5	31.3°
Bakersfield (B)	35.356	119.058	2.814	312.9	227.2°
Reno (RFNB)	39.526	119.812	3.401	378.2	311.8°
Los Angeles (UB)	34.053	118.256	3.531	392.6	22.9°
Sacramento (SWR)	38.576	121.497	4.125	458.6	289.5°
Salt Lake City (SLC)	40.748	111.872	5.002	556.2	45.1°

TABLE 2. STATION LOCATIONS, DISTANCES, AND AZIMUTHS FOR EVENT BOXCAR

Latitude 37.30°N, Longitude 116.45°W
April 26, 1968
15:00:00.1 GMT

Station	Site Coordinates °N	Site Coordinates °W	Distance Deg.	Distance Km	Azimuth Epicenter to Station
Pioche (P)	37.937	114.450	1.717	190.9	67.5°
Austin (A)	39.490	117.070	2.247	249.9	347.8°
San Francisco (SF)	37.803	122.399	4.751	528.2	277.9°
Ogden (OG)	41.233	111.917	5.279	587.0	40.5°
Edmonton (EDM)	53.222	113.350	16.072	1787.2	6.7°
Fort St. James (FSJ)	54.433	124.250	17.959	1997.0	345.1°
Flin Flon (FFC)	54.725	101.934	20.065	2231.2	25.1°
Oxford (OXF)	34.512	89.409	22.059	2452.3	89.1°
Spring Hill (SHA)	30.693	88.384	24.131	2683.2	97.5°
Ann Arbor (AAM)	42.301	83.657	25.590	2845.5	68.5°
Atlanta (ATL)	33.434	84.336	26.401	2935.7	88.7°
Blacksburg (BLA)	37.211	80.422	28.572	3177.1	79.1°
Baker Lake (BLC)	64.316	95.017	29.941	3329.3	18.6°
Coppermine (CMC)	67.834	115.083	30.599	3402.4	1.0°
Georgetown (GEO)	38.900	77.066	30.875	3433.1	74.8°
Great Whale River (GWC)	55.291	77.756	31.688	3523.5	42.9°
Ogdenburg (OGD)	41.066	74.617	32.422	3605.1	70.2°
College (COL)	64.900	147.800	33.257	3698.1	336.1°
Weston (WES)	42.385	71.320	34.709	3859.9	67.2°
Mould Bay (MBC)	76.242	119.333	39.065	4343.8	358.9°
Alert (ALE)	82.484	62.400	48.721	5417.5	8.2°

TABLE 3. STATION LOCATIONS, DISTANCES, AND AZIMUTHS FOR EVENT BENHAM

Latitude 37.23°N, Longitude 116.47°W
December 19, 1968
16:30:00:04 GMT

Station	Site Coordinates °N	Site Coordinates °W	Distance Deg.	Distance Km	Azimuth Epicenter to Station
Squires Park (SP)	36.174	115.139	1.505	167.4	134.1°
Ely (ELY)	39.131	114.892	2.269	252.3	32.8°
Bakersfield (B)	35.356	119.058	2.804	311.8	228.9°
Reno (RA)	39.508	119.021	3.028	336.7	319.4°
Los Angeles (UB)	34.053	118.256	3.488	387.9	205.1°
Sacramento (SWR)	38.576	121.497	4.193	466.2	290.2°
Salt Lake City (SLC)	40.743	111.872	5.017	558.9	44.2°
Corvallis (COR)	44.586	123.302	8.982	999.7	327.0°
Fort St. James (FSJ)	54.433	124.250	18.018	2003.5	345.2°
Oxford (OXF)	34.512	89.409	22.071	2454.2	88.9°
Yellow Knife (YKC)	62.478	114.478	25.304	2813.7	2.2°
Ann Arbor (AAM)	42.301	83.657	25.629	2849.8	68.4°
Blacksburg (BLA)	37.211	80.422	28.600	3180.2	79.0°
State College Penn (SCP)	40.795	77.867	30.045	3340.9	71.1°
Coppermine (CMC)	38.900	77.066	30.664	3409.7	1.0°
Ottawa (OTT)	45.393	75.715	31.405	3492.1	62.0°

TABLE 4. STATION LOCATIONS, DISTANCES, AND AZIMUTHS FOR EVENT FAULTLESS

Latitude 38.634°N, Longitude 116.215°W
January 19, 1968
18:15:00.08 GMT

Station	Site Coordinates		Distance		Azimuth
	°N	°W	Deg.	Km	Epicenter to Station
Eureka (EKA)	39.483	115.970	0.869	96.6	12.6°
Pioche (P)	37.937	114.450	1.554	172.8	116.1°
Reno (RA)	39.508	119.776	2.906	323.1	288.6°
Fresno (FSO)	36.729	119.822	3.436	382.0	237.5°
Great Salt Lake Fill (GSLF)	41.220	112.642	3.770	419.2	45.6°
Bakersfield (B)	35.356	119.058	3.986	443.2	215.7°
Sacramento (CTPN)	38.521	121.492	4.137	460.0	270.1°
Ogden (OG)	41.233	111.917	4.202	467.2	50.5°
Los Angeles (BSC)	34.090	118.339	4.848	539.1	201.3°
San Francisco (SF)	37.803	122.399	4.991	549.9	262.2°
Salt Lake City (SLC)	40.748	111.872	5.002	556.2	45.1°
Edmonton (EDM)	53.222	113.350	14.724	1627.2	6.8°
Fort St. James (FSJ)	54.433	124.250	16.724	1859.7	343.5°
Oxford (OXF)	34.512	89.409	21.883	2433.3	92.6°
Yellowknife (YKC)	62.478	114.478	23.897	2657.3	2.0°
Spring Hill (SHA)	30.693	98.384	24.155	2685.9	100.7°
Ann Arbor (AAM)	42.301	83.657	24.951	2774.4	71.1°
Blacksburg (BLA)	37.211	80.422	28.161	3121.3	81.6°
Baker Lake (BLC)	64.316	95.017	28.616	3182.0	19.2°
Ogdenburg (OGD)	41.066	74.617	31.811	3537.3	72.2°
Weston (WES)	42.385	71.320	34.036	3784.6	69.1°

3
S-WAVE OBSERVATIONS

As found by Nuttli, it is often difficult to observe S waves at short distances. The three-component seismograms reproduced in Figs. 9-16 show the extreme variation between the clear arrivals at greater distances and the complex seismograms obtained at the shorter first-zone distances (< 250 km). However, it is also shown that for some events at some close-in stations, very clear S waves of both SV and SH types are observable.

The strong SH arrivals are the most significant finding from this work. These waves are generated at the source since they cannot be created at geologic interfaces along the propagation path.

The seismograms show that most of the clear S wave arrivals are SV types propagated directly from the explosive source. However, because the travel time of the SV waves is so close to that of the SH waves, one must conclude that at least the major part of the path was traversed as an S wave. It is well known [5, 6, 7, 8] that one should not expect rectilinear SV particle motion at distances less than approximately 41°. However, rectilinear motion was observed and the corresponding arrival times plotted in Figs. 17 and 18 are in several cases consistent with the arbitrarily selected model. This leads one to conclude that the S waves at these distances travel refracted ray paths and therefore arrive at the surface at small angles of incidence, thus producing in-phase motion between the radial and vertical components. The fact that rectilinear motion was observed frequently, and at consistent times, should not be construed as an indication of tectonic strain release at the source. Because SV waves can be generated by P-wave reflection, those arrivals that deviate greatly from the model may be P-wave generated.

The amplitudes appearing in Tables 5 through 7 were measured on the WWSSN and Canadian records in accordance with the criteria prescribed by Nuttli [9] in 1968. They are included herein only for comparison with the first zone amplitudes given in Tables 8 through 11. Analysis of this type of data has been performed by Nuttli (1969) and is not duplicated here. These data could also form the basis for study of a P-wave/S-wave discriminate and it is suggested that such work be started.

It should be noted that the records obtained at the WWSSN and Canadian stations show "strong" signals for the three events, whereas the first-zone records vary considerably from event to event. To cite an example of the latter variation: BOXCAR shows clear S arrivals at Pioche and Austin, as does HANDLEY at Pahrump and Squires Park; but the BENHAM first-zone records so not reveal any clear S waves.

The seismograms (Figs. 9-16) also show that in several cases where no S waves are evident at first-zone distances, they become observable along the approximate same azimuth at

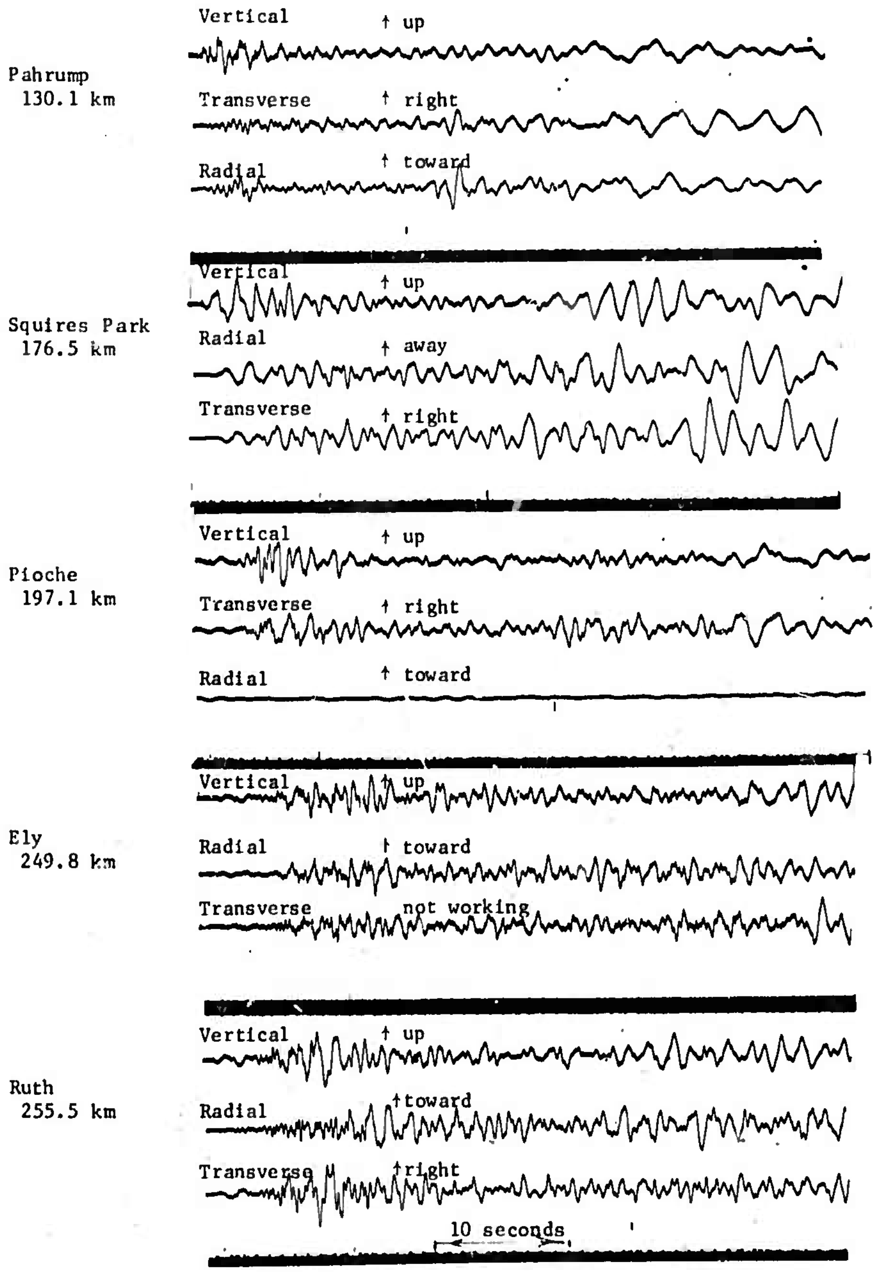

FIGURE 9. THREE-COMPONENT SEISMOGRAMS FROM HANDLEY (FIRST-ZONE STATIONS). The words "right," "toward," and "away" are in reference to an observer at the station facing the epicenter.

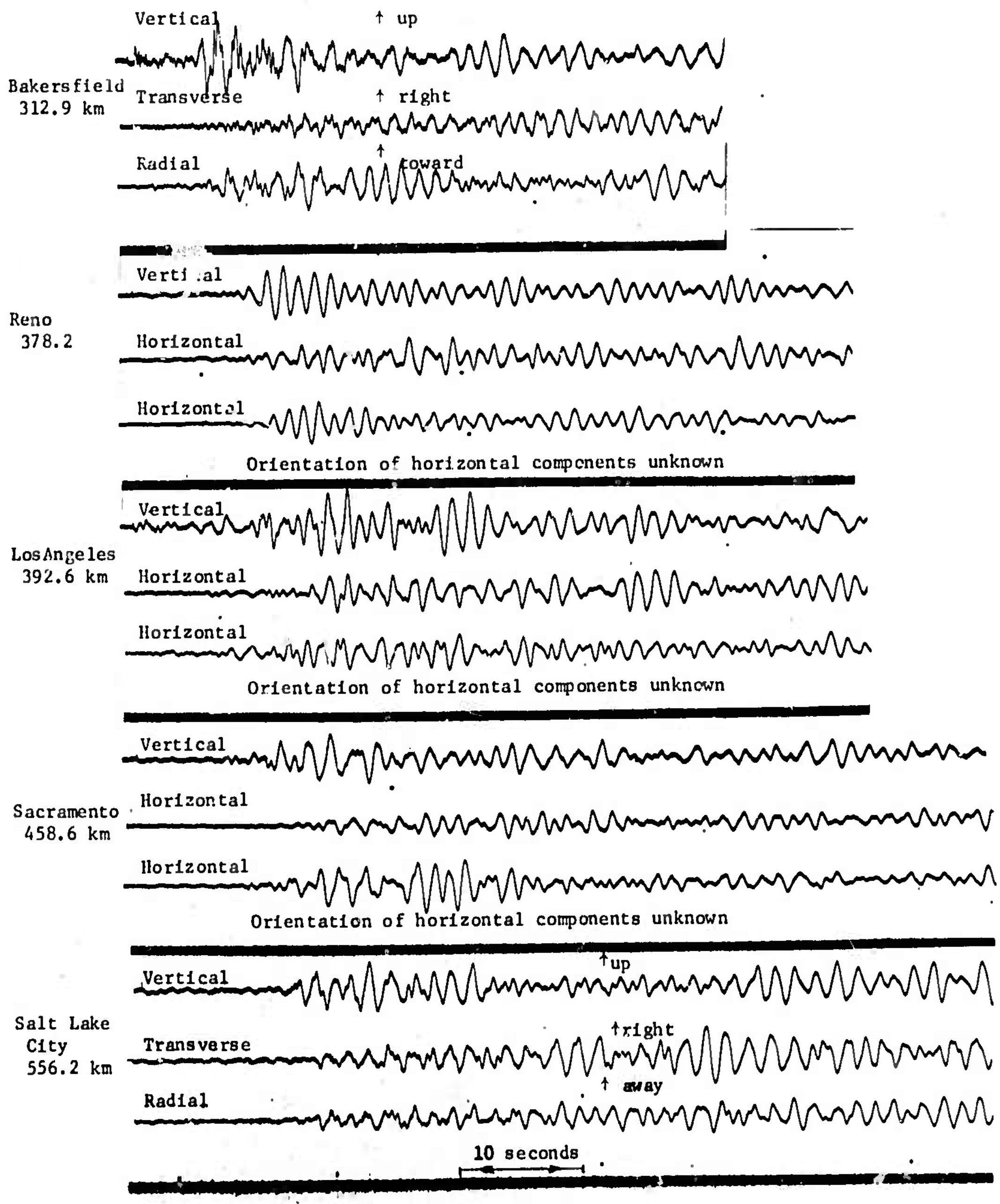

FIGURE 10. THREE-COMPONENT SEISMOGRAMS FROM HANDLEY (FIRST-ZONE STATIONS). The words "right," "toward," and "away" are in reference to an observer at the station facing the epicenter.

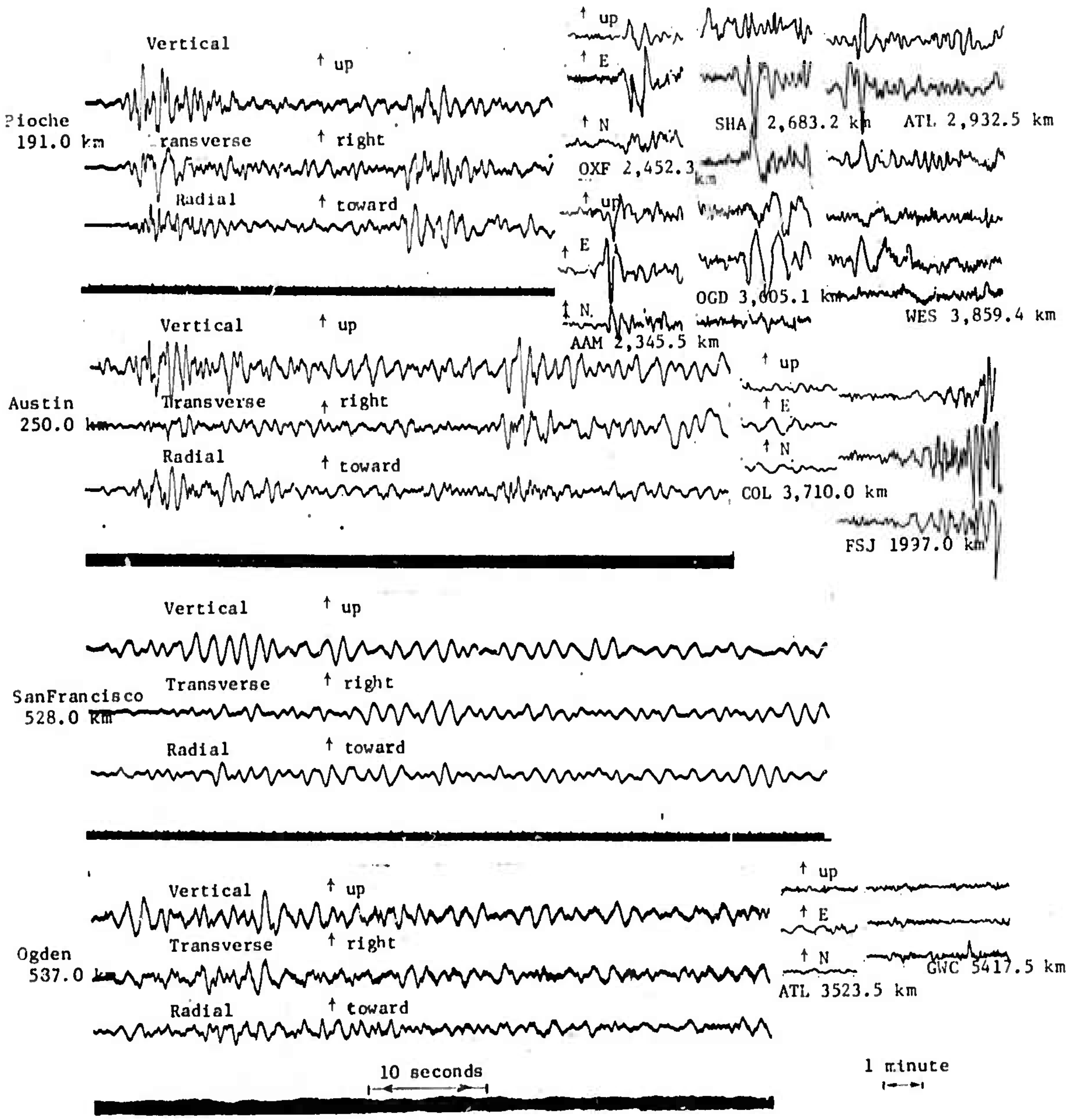

FIGURE 11. THREE-COMPONENT FIRST-ZONE AND WWSSN SEISMOGRAMS FROM BOXCAR. The WWSSN seismogram shown here lies approximately on the same azimuth as the accompanying first-zone seismograms. The words "right," "toward," and "away" are in reference to an observer at the station facing the epicenter.

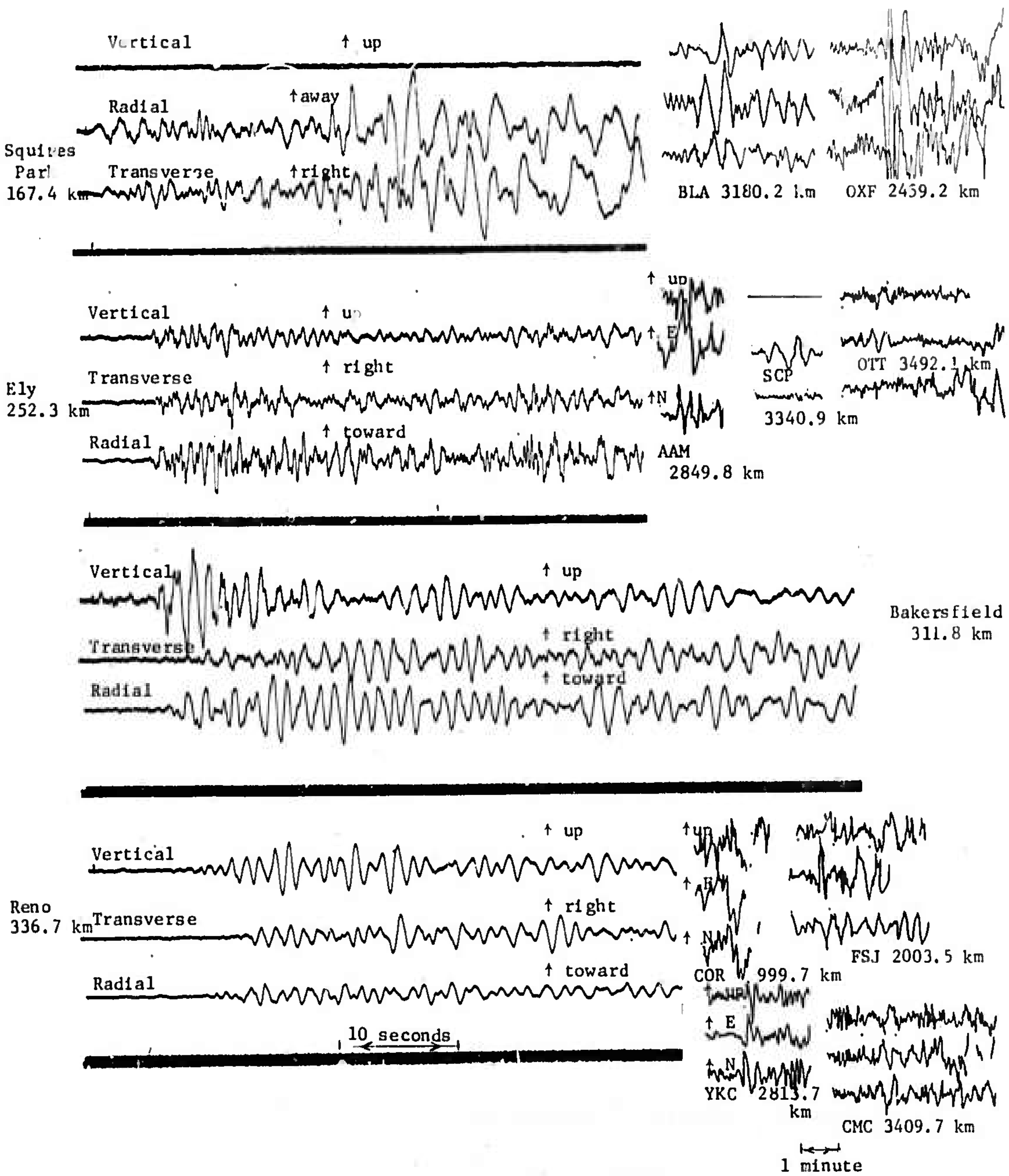

FIGURE 12. THREE-COMPONENT FIRST-ZONE AND WWSSN SEISMOGRAMS FROM BENHAM. The WWSSN seismograms lie approximately on the same azimuth as the accompanying first-zone seismograms. The words "right," "toward," and "away" are in reference to an observer at the station facing the epicenter.

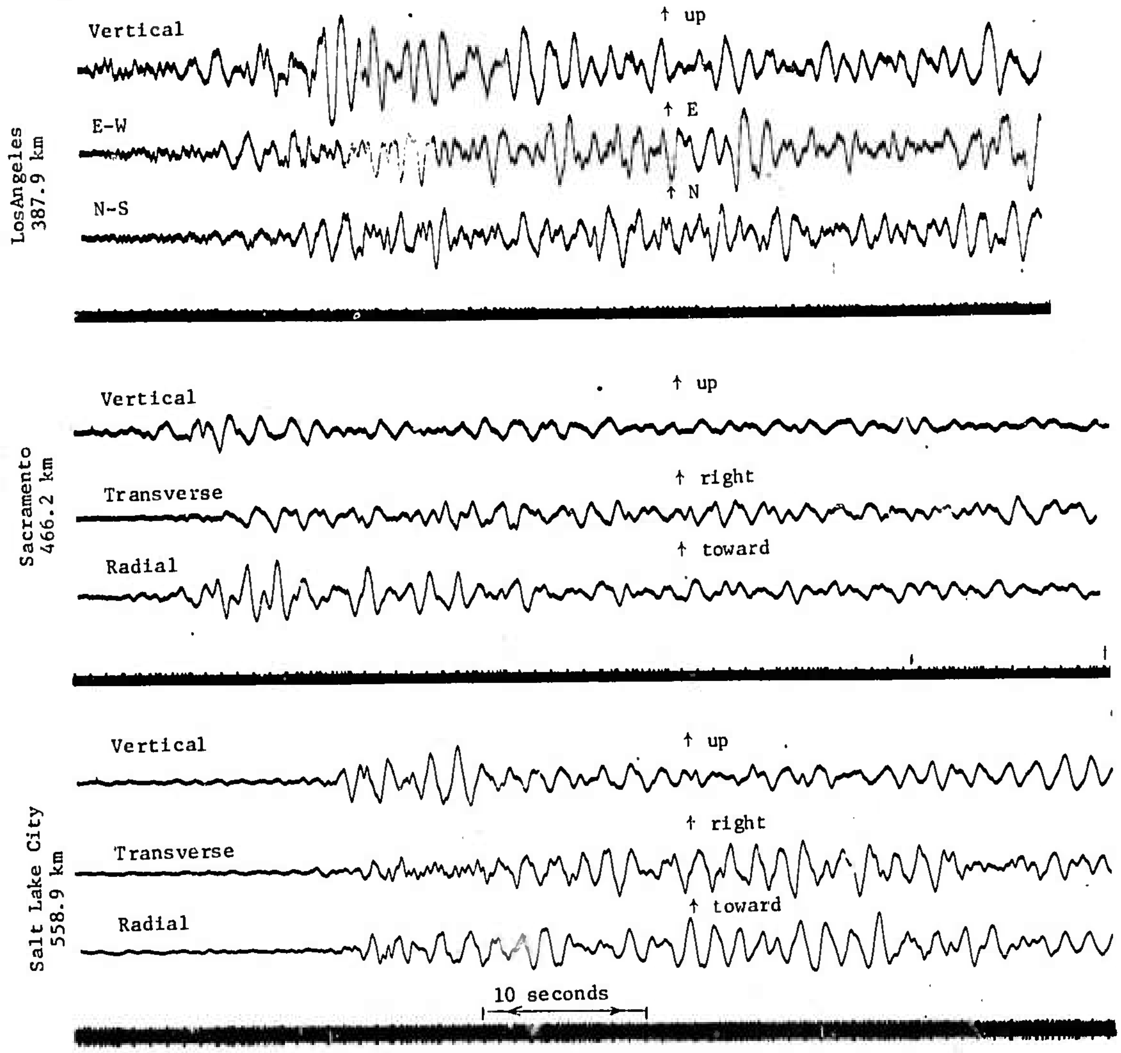

FIGURE 13. THREE-COMPONENT FIRST-ZONE SEISMOGRAMS FROM BENHAM. The words "right," "toward," and "away" are in reference to an observer at the station facing the epicenter.

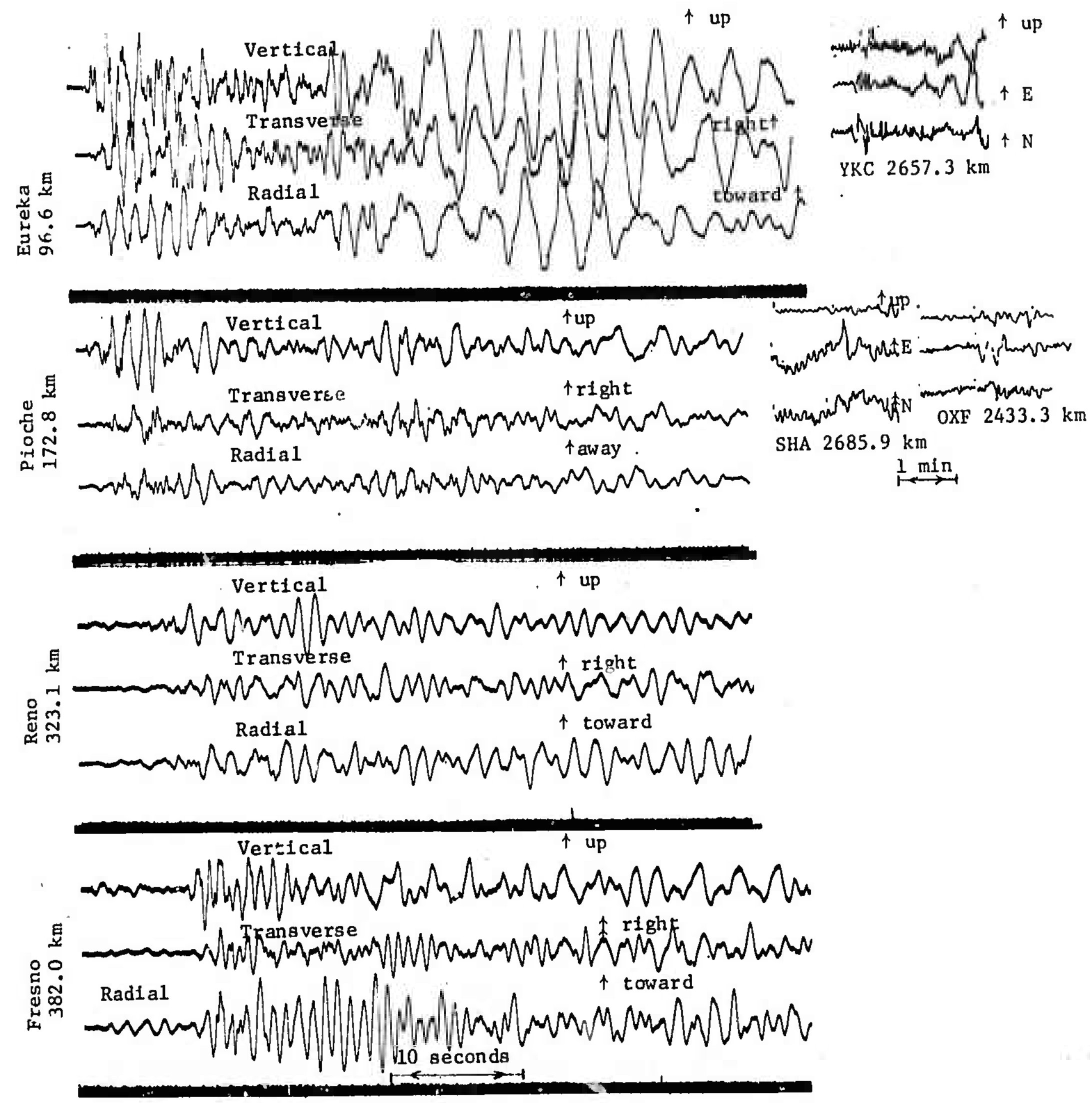

FIGURE 14. THREE-COMPONENT FIRST-ZONE AND WWSSN SEISMOGRAMS FROM FAULTLESS. The WWSSN seismograms lie approximately on the same azimuth as the accompanying first-zone seismograms. The words "right," "toward," and "away" are in reference to an observer at the station facing the epicenter.

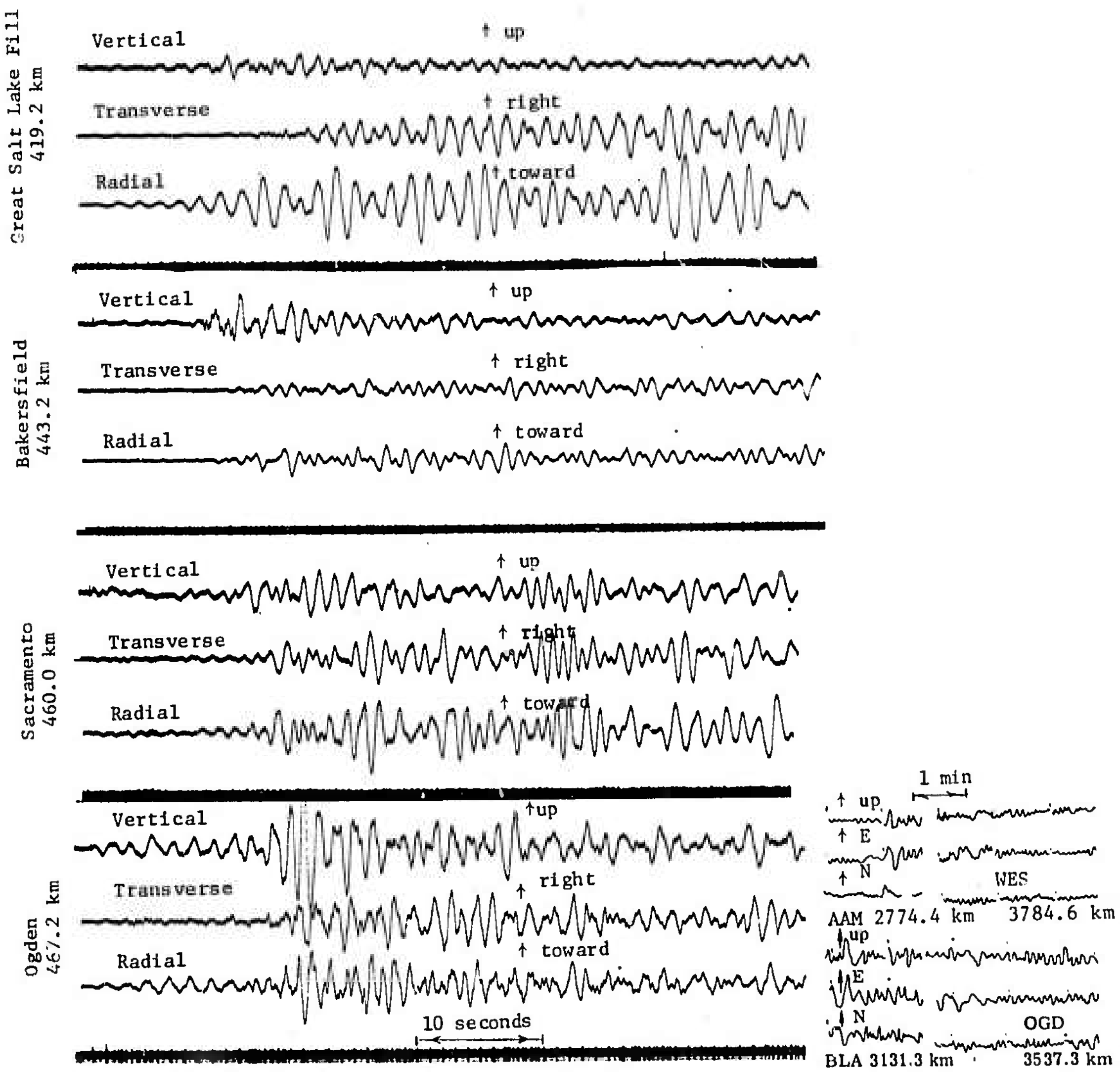

FIGURE 15. THREE-COMPONENT FIRST-ZONE AND WWSSN SEISMOGRAMS FROM FAULTLESS. The WWSSN seismograms lie on approximately the same azimuth as the accompanying first-zone seismograms. The words "right," "toward," and "away" are in reference to an observer at the station facing the epicenter.

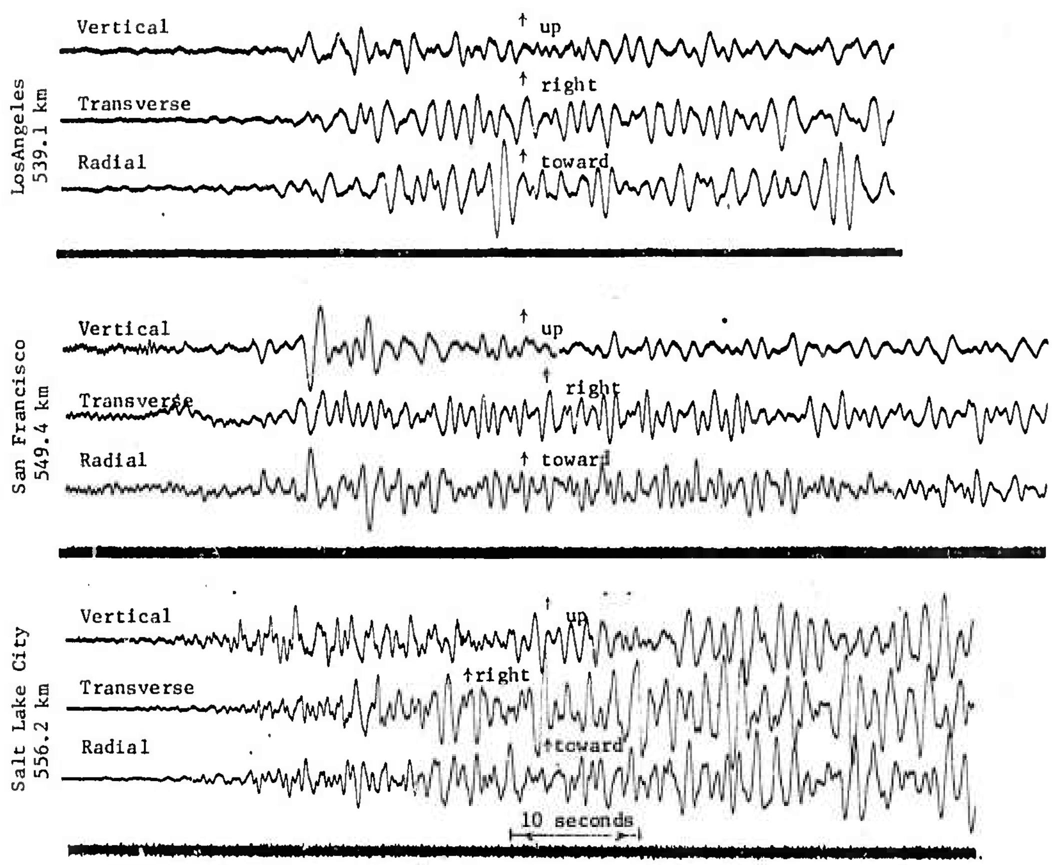

FIGURE 16. THREE-COMPONENT FIRST-ZONE SEISMOGRAMS FOR FAULTLESS
The words "right," "toward," and "away" are in reference to an observer at the station facing the epicenter.

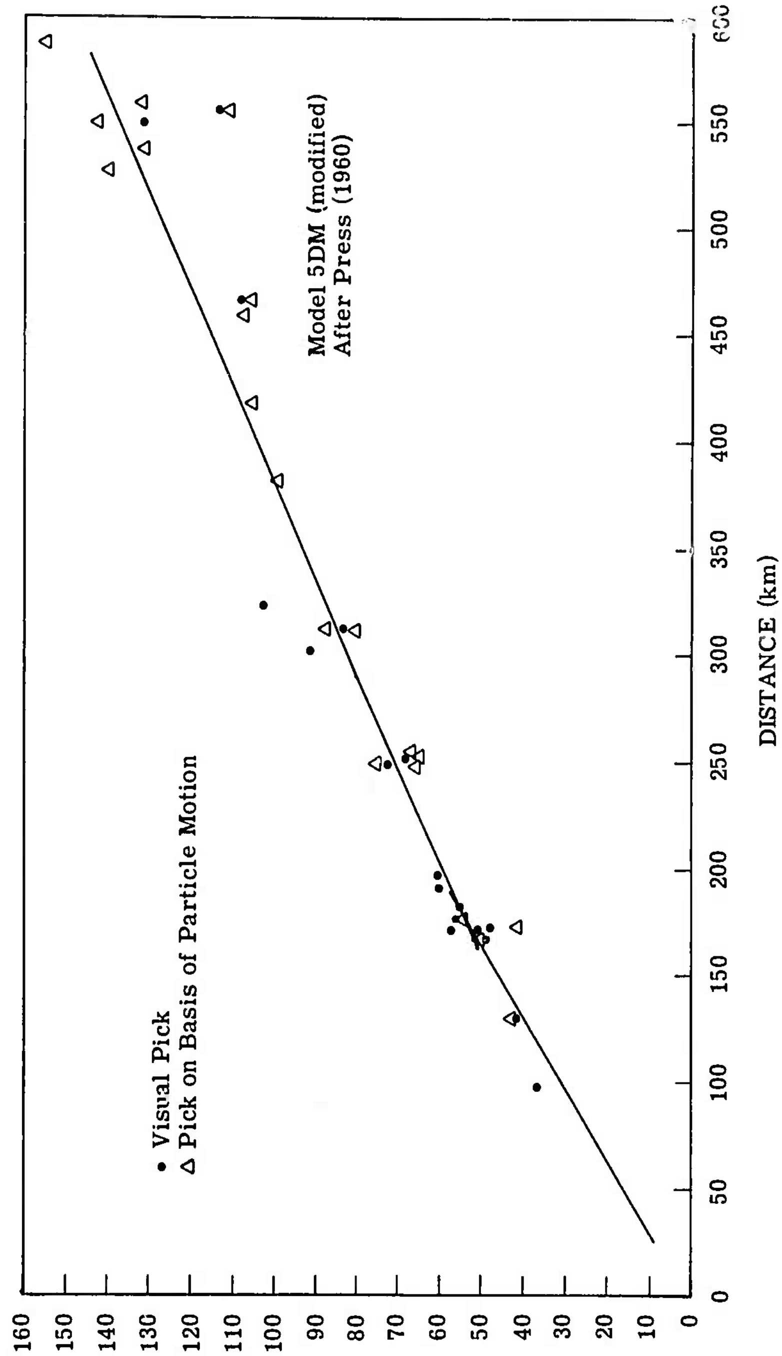

FIGURE 17. SV TRAVEL TIME DATA

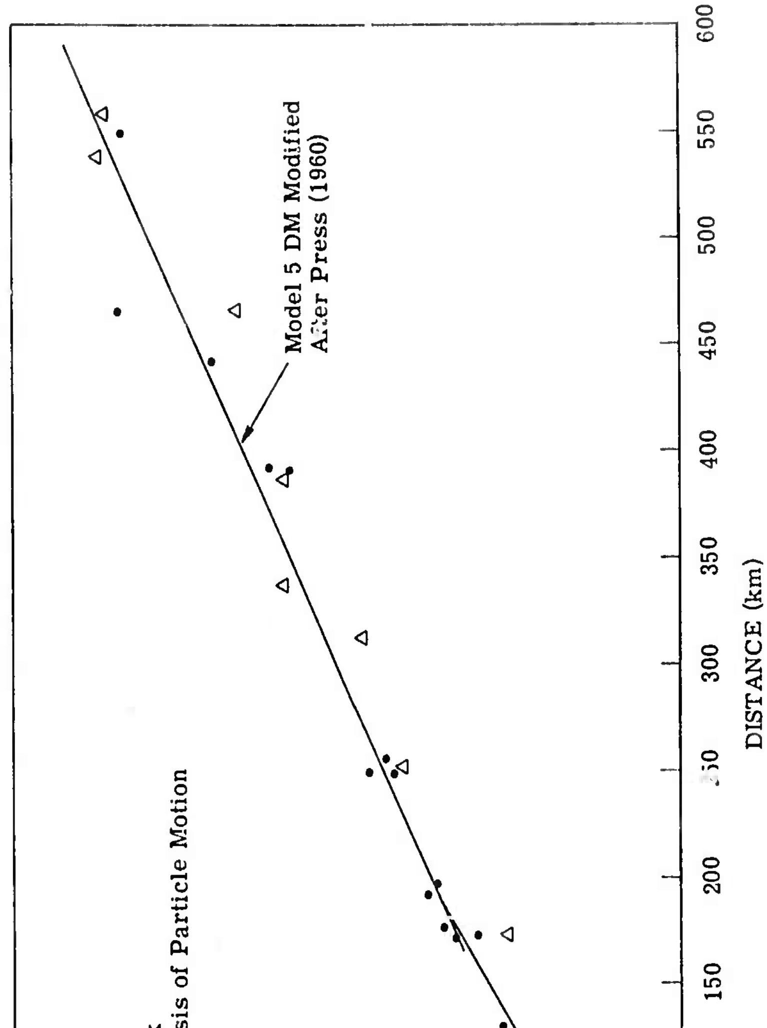

FIGURE 18. SH TRAVEL TIME DATA

TABLE 5. BOXCAR TRAVEL TIMES, AMPLITUDES, AND PERIODS OF S WAVES AT WWSSN AND CANADIAN NETWORK STATIONS

Station	Distance (deg)	Distance (km)	Azimuth Epicenter to Station (deg)	Component	Travel Time (min:sec)	Amplitude (μ)	Period (sec)
FSJ	17.96	1997	345.1	Z	7:52	1.6	16
				NS	7:48	1.0	9
				EW	7:54	1.3	8
OXF	22.05	2452	89.1	Z	9:09	3.4	12
				NS	9:07	1.1	14
				EW	9:09	5.5	16
SHA	24.13	2683	97.5	Z	9:58	6.7	16
				NS	9:50	2.1	12
				EW	9:48	9.6	22
AAM	25.59	2846	68.5	Z	10:16	4.6	6
				NS	10:16	3.4	6
				EW	10:03	2.9	16
FCC	25.94	2884	27.0	Z	10:11	0.9	16
				NS	10:08	1.2	16
				EW	10:03	2.9	20
ATL	26.40	2936	88.7	Z	10:12	1.6	10
				NS	10:12	0.8	20
				EW	10:11	1.5	14
BLA	28.57	3177	79.1	Z	11:04	2.2	32
				NS	10:55	0.6	12
				EW	10:52	4.5	14
BLC	29.94	3329	18.6	Z	11:20	6.6	24
				N	11:06	1.3	20
				E	11:16	0.5	26
CMC	30.60	3402	1.0	Z	11:32	0.2	32
				NS	11:32	0.2	24
				EW	11:28	1.1	32
GEO	30.88	3433	74.8	Z	11:41	3.4	24
				NS	NRS	NRS	NRS
				EW	11:17	14.6	26

TABLE 5. BOXCAR TRAVEL TIMES, AMPLITUDES, AND PERIODS OF S WAVES AT WWSSN AND CANADIAN NETWORK STATIONS (Continued)

Station	Distance (deg)	Distance (km)	Azimuth Epicenter to Station (deg)	Component	Travel Time (min:sec)	Amplitude (μ)	Period (sec)
GWC	31.69	3524	42.9	Z	12:00	0.4	40
				NS	11:40	0.4	16
				EW	11:40	0.2	16
OGD	32.42	3605	70.2	Z	12:03	1.8	38
				NS	12:00	0.3	14
				EW	11:54	2.7	18
COL	33.40	3710	338.0	Z	12:00	0.8	24
				NS	12:06	1.2	24
				EW	12:08	0.8	20
WES	34.71	3859	67.2	Z	12:36	3.1	40
				NS	NRS*	NRS	NRS
				EW	12:30	3.6	14
MBC	39.07	4344	358.9	Z	13.44	1.3	40
				NS	13.34	1.2	24
				EW	NRS	NRS	NRS
ALE	48.72	5418	8.2	Z	NRS	NRS	NRS
				NS	NRS	NRS	NRS
				EW	15:40	0.3	24

*NRS--Signal not readable in noise

TABLE 6. BENHAM TRAVEL TIMES, AMPLITUDES, AND PERIODS OF S WAVES AT WWSSN AND CANADIAN NETWORK STATIONS

Station	Distance (deg)	Distance (km)	Azimuth Epicenter to Station (deg)	Component	Travel Time (min:sec)	Amplitude (μ)	Period (sec)
FSJ	18.02	2004	345.2	Z	7:46	3.1	8
				NS	7:42	6.8	12
				EW	7:34	5.4	32
OXF	22.07	2454	88.9	Z	8:56	2.0	12
				NS	8:56	2.2	10
				EW	9:00	1.8	14
YKC	25.30	2814	2.2	Z	10:10	1.1	12
				NS	10:18	2.3	20
				EW	10:06	1.3	36
AAM	25.63	2850	68.4	Z	10:18	6.7	10
				NS	10:18	8.1	12
				EW	10:17	5.3	6
BLA	28.60	3180	79.0	Z	11:02	2.5	30
				NS	10:55	2.9	16
				EW	10:51	4.7	14
SCP	30.05	3341	71.1	Z	NA	NA	NA
				NS	NRS	NRS	NRS
				EW	11:15	3.0	12
CMC	30.66	3410	1.0	Z	11:42	2.7	8
				NS	11:36	0.9	24
				EW	11:30	1.0	20
OTT	31.41	3492	62.0	Z	12:00	1.8	24
				NS	NRS	NRS	NRS
				EW	11:44	2.7	24

NA--Data not available.
NRS--Signal not readable in noise.

TABLE 7. FAULTLESS TRAVEL TIMES, AMPLITUDES, AND PERIODS OF S WAVES AT WWSSN AND CANADIAN NETWORK STATIONS

Station	Distance (deg)	Distance (km)	Azimuth Epicenter to Station (deg)	Component	Travel Time (min:sec)	Amplitude (μ)	Period (sec)
FSJ	16.72	1860	343.0	Z	7:18	1.5	8
				NS	NRS	NRS	NRS
				EW	7:18	8.6	6
OXF	21.88	2433	92.6	Z	9:05	0.9	8
				NS	9:00	0.8	20
				EW	9:05	2.5	16
YKC	23.90	2657	2.0	Z	9:38	2.5	8
				NS	9:32	3.1	16
				EW	9:36	2.1	8
SHA	24.16	2686	100.7	Z	10:10	1.1	20
				NS	10:05	5.1	16
				EW	9:56	5.9	12
AAM	24.95	2774	21.1	Z	10:00	1.6	14
				NS	10:08	3.1	12
				EW	10:00	4.2	18
BLA	28.15	3131	81.6	Z	10:53	0.4	8
				NS	11:05	0.8	24
				EW	10:45	2.2	10
BLC	28.62	3182	19.2	Z	11:14	1.4	12
				NS	10:48	1.2	24
				EW	11:09	1.1	16
OGD	31.8[illegible]	3537	72.2	Z	12:05	1.4	30
				NS	NRS	NRS	NRS
				EW	11:43	1.7	10
WES	34.04	3785	69.1	Z	12:33	0.3	20
				NS	NRS	NRS	NRS
					12:13	0.4	12

NRS--Signal not readable with noise.

TABLE 8. HANDLEY TRAVEL TIMES, AMPLITUDES, AND PERIODS OF S WAVES AT FIVE FIRST-ZONE STATIONS

Station	Distance (deg)	Distance (km)	Azimuth Epicenter to Station (deg)	Component	Travel Time (min:sec)	Amplitude (μ)	Period (sec)
Pahrump (PN)	1.170	130.1	157.6	Z	--	--	--
				NS	41.2	420	1.3
				EW	42.0	420	1.2
Squires Park (SP)	1.587	176.5	134.7	Z	--	--	--
				NS	55.3	1680	2.2
				EW	56.1	1080	2.0
Pioche (P)	1.773	197.1	68.4	Z	1:00.2	108	1.2
				NS	--	--	--
				EW	58.7	44	0.8
Ely (ELY)	2.239	249.0	34.8	Z	--	--	--
				NS	--	--	--
				EW	1:08.1	101	1.2
Ruth (R)	2.298	255.5	31.3	Z	--	--	--
				NS	--	--	--
				EW	1:10.1	89	1.4

TABLE 9. BENHAM TRAVEL TIMES, AMPLITUDES, AND PERIODS OF S WAVES AT TWO FIRST-ZONE STATIONS

Station	Distance (deg)	Distance (km)	Azimuth Epicenter to Station (deg)	Component	Travel Time (min:sec)	Amplitude (μ)	Period (sec)
Squires Park (SP)	1.505	167.4	134.1	Z	--	--	
				NS	49.8	360	1.2
				EW	--	--	--
Ely (ELY)	2.269	252.3	32.8	Z	--	--	--
				NS	1:08.4	51	0.8
				EW	--	--	--

TABLE 10. BOXCAR TRAVEL TIMES, AMPLITUDES, AND PERIODS OF S WAVES AT ALL FIRST-ZONE STATIONS

Station	Distance (deg)	Distance (km)	Azimuth Epicenter to Station (deg)	Component	Travel Time (min:sec)	Amplitude (μ)	Period (sec)
Pioche (P)	1.717	190.9	67.5	Z	59.9	36.4	1.0
				NS	1:00.1	176.0	1.1
				EW	59.7	84.0	1.0
Austin (A)	2.247	249.9	347.8	Z	1:14.1	64.2	1.4
				NS	--	--	--
				EW	1:13.8	45.1	1.2
San Francisco (SF)	4.751	528.2	277.9	--	--	--	--
Ogden (OG)	5.279	587.0	40.5	Z	--	--	--
				NS	2:34.2	3.4	1.6
				EW	--	--	--

TABLE 11. FAULTLESS TRAVEL TIMES, AMPLITUDES, AND PERIODS OF S WAVES AT TEN FIRST-ZONE STATIONS

Station	Distance (deg)	Distance (km)	Azimuth Epicenter to Station (deg)	Component	Travel Time (min:sec)	Amplitude (μ)	Period (sec)
Eureka (EKA)	0.869	96.6	12.6	Z	36.5	710	1.4
				NS	36.5	560	1.4
				EW	35.9	890	1.4
Pioche (P)	1.554	172.8	116.1	Z	47.4	400	1.4
				NS	--	--	--
				EW	47.7	204	1.4
Reno (RA)	2.906	323.1	288.6	--	--	--	--
Fresno (FSO)	3.436	382.0	237.5	Z	--	--	--
				NS	39.3	20	1.4
				EW	--	--	--
Great Salt Lake Fill (GSLF)	3.770	419.2	45.6	--	--	--	--
Bakersfield (B)	3.986	443.2	215.7	Z	--	--	--
				NS	50.7	17	1.2
				EW	51.4	7.8	1.2
Sacramento (CTPN)	4.137	460.0	270.1	--	--	--	--
Ogden (OG)	4.202	467.2	50.5	Z	--	--	--
				NS	45.8	8.4	1.4
				EW	46.0	7.2	1.2
San Francisco (SF)	4.991	549.9	262.2	Z	2:10.52	6.5	2.4
				NS	--	--	--
				EW	2:12.42	2.7	1.0
Salt Lake City (SLC)	5.002	556.2	45.1	Z	1:52.62	32	1.6
				NS	1:52.62	46	1.2
				EW	--	--	--

the greater ranges of WWSSN and Canadian stations. For example, while the BENHAM first-zone records (Fig. 13) do not show any clear S waves, the WWSSN and Canadian stations (Fig. 12) show strong S arrivals for the same event. The FAULTLESS records (Figs. 14-16) show some fair S waves at nearby Eureka and Pioche but these are certainly not as strong as in the BOX-CAR and HANDLEY records cited above.

Travel time data is tabulated and graphed (Figs. 17 and 18) to aid in S-wave identification. The travel time curve for Press's model (1960) of the California-Nevada region [10] provided a guide; his model 5 DM was used with the modification described in the same text. No crustal or mantle structure interpretation is given in the present report.

Particle motion diagrams of all first-zone records were constructed in an attempt to detect S-wave motion where none could be seen by inspection. Although the specific types of motion comprising S waves are not known, one should hope to see rectilinear SH motion, rectilinear SV motion due to small angles of incidence, or the shear-coupled PL elliptical motion. In the latter case, one would identify the very first elements of the elliptical motion as the S wave. Several cases of rectilinear motion at small angles of incidence were found.

4
P-WAVE STUDIES

P-wave travel times from each event have been plotted (Fig. 19) to make sure that the identification was correct and to show that every station received a P-wave signal even though no S wave was recorded at many stations (particularly for the BENHAM event). P-wave polarity (+ for earth motion up,—for earth motion down) is indicated in Figs. 1, 3, 5, and 7.

5
CONCLUSIONS

Good SH arrivals at first-zone distances were observed from the FAULTLESS, BOXCAR, and HANDLEY explosions. From BENHAM, on the other hand, no good SH or SV arrivals were seen at such distances, despite the fact that WWSSN stations show strong SH waves for BENHAM (as well as for FAULTLESS and BOXCAR). At WWSSN and Canadian stations along the same azimuth as first-zone stations, good SH arrivals are noted for BENHAM whereas the first-zone stations did not receive good signals.

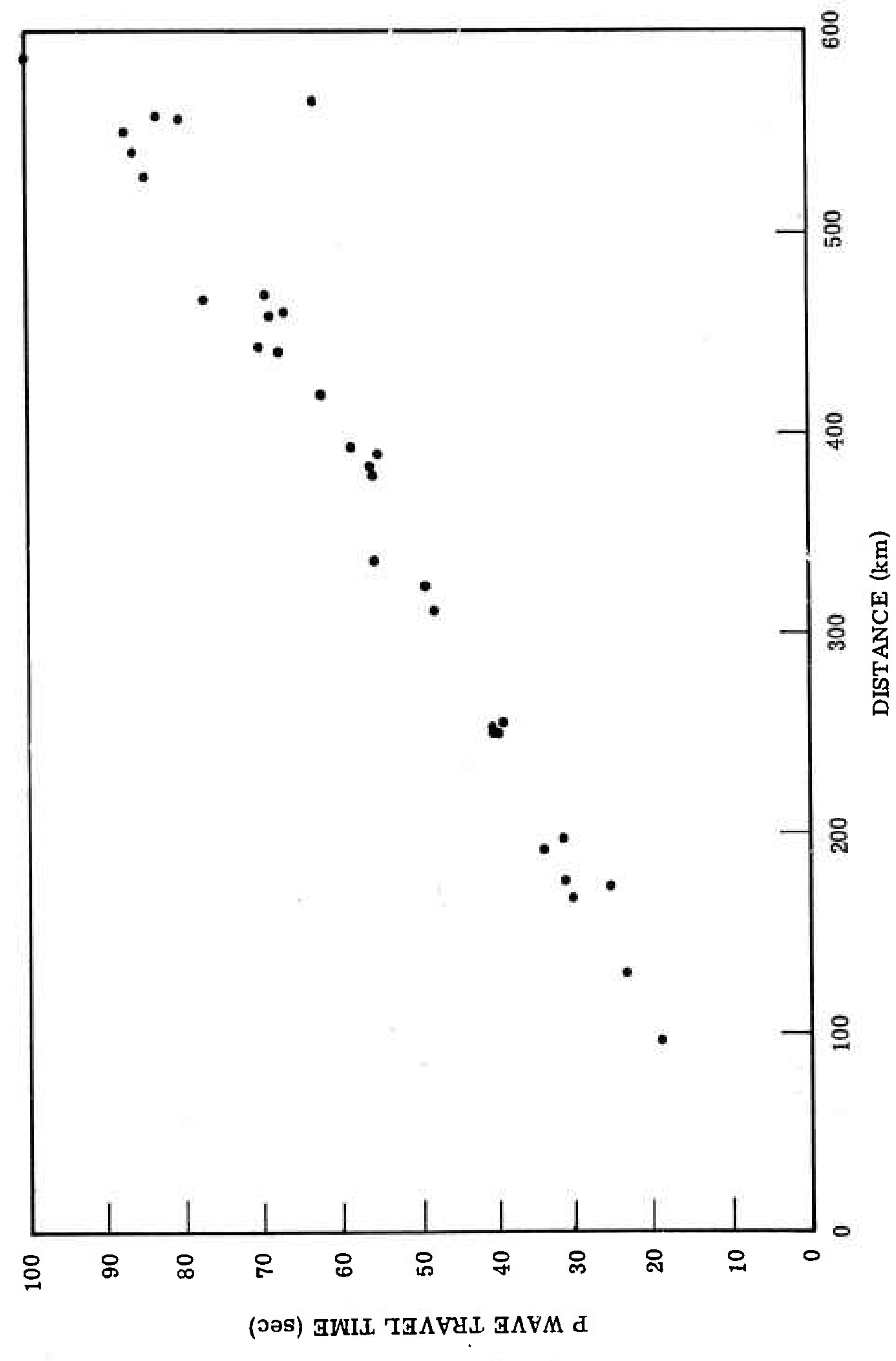

FIGURE 19. P-WAVE TRAVEL-TIME CURVE FOR ALL EVENTS AS MEASURED AT THE FIRST-ZONE STATIONS

Attempts were made to observe SV and SH waves under very poor signal-to-noise conditions. Rectilinear particle motion for the SV wave was assumed and all records were scanned for such motion. Results were deemed moderately successful.

Despite several good SH recordings,* these were too few to warrant plotting radiation patterns. However, several P-wave rarefaction first motions were observed and plotted. These observations qualitatively agree with the fact that several good SH records were observed.

In general, the data tend to indicate that the events FAULTLESS, BOXCAR, and HANDLEY may have produced some release of tectonic strain. For event BENHAM, the first-zone data are less conclusive.

*It must be understood that SH waves could also be generated by explosions in nonspherical cavities [11].

REFERENCES

1. Navarro, R., et al., U.S. Coast and Geodetic Survey Seismograph Systems, U.S. Department of Commerce, Rockville, Maryland, 1967.

2. Preliminary Calibration of the SCATT-1 System CGS-C-119, Envir. Scien. Ser. Admin., U.S. Dept. of Commerce, Rockville, Maryland, 1968.

3. Handbook: World-Wide Standard Seismograph Network, Willow Run Laboratories of the Institute of Science and Technology, The University of Michigan, 1966.

4. For calibration curves, Canadian Seismic Stations:
   a. Seismological Bulletin, Jan-Dec, Dominion Observatory, Dept. of Energy, Mines and Resources, Ottawa, Ont., 1968.
   b. Seismological Series of the Dominion Observatory, Dept. of Energy, Mines and Resources, Ottawa, Ontario, 1969.

5. Nuttli, O., The Effect of the Earth's Surface on the S-Wave Particle Motion, Bull. Seism. Soc. Am., Vol. 51, No. 2, 1961.

6. Nuttli, O. and J. Whitmore, On the Determination of the Polarization Angle of the S Wave, Bull. Seism. Soc. Am., Vol. 52, No. 1, 1962.

7. Nuttli, O., The Determination of S-Wave Polarization Angles for an Earth Model with Crustal Layering, Bull. Seism. Soc. Am., Vol. 54, No. 5, Part A, 1964.

8. Ibrahm, A. and O. Nuttli, Travel-Time Curves and Upper Mantle Structure from Long Period S Waves, Bull. Seism. Soc. Am., Vol. 57, No. 5, 1967.

9. Nuttli, O., Travel-Times and Amplitudes of S Waves from Nuclear Explosions in Nevada, Bull. Seism. Soc. Am., Vol. 59, No. 1, 1969.

10. Press, F., Crustal Structure in the California-Nevada Region, J. Geophys. Res., Vol. 65, No. 3, 1960.

11. Gupta, I. N. and C. Kisslinger, Model Studies of Seismic Waves from Explosions in Rectangular Cavities, Bull. Seism. Soc. Am., Vol. 54, 1964.